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Application of Environmental Seismic Intensity scale (ESI 2007) to Krn Mountains 1998 $M_w = 5.6$ earthquake (NW Slovenia) with emphasis on rockfalls

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Abstract. The 12 April 1998 $M_w = 5.6$ Krn Mountains earthquake with a maximum intensity of VII–VIII on the EMS-98 scale caused extensive environmental effects in the Julian Alps. The application of intensity scales based mainly on damage to buildings was limited in the epicentral area, because it is a high mountain area and thus very sparsely populated. On the other hand, the effects on the natural environment were prominent and widespread. These facts and the introduction of a new Environmental Seismic Intensity scale (ESI 2007) motivated a research aimed to evaluate the applicability of ESI 2007 to this event. All environmental effects were described, classified and evaluated by a field survey, analysis of aerial images and analysis of macroseismic questionnaires. These effects include rockfalls, landslides, secondary ground cracks and hydrogeological effects. It was realized that only rockfalls (78 were registered) are widespread enough to be used for intensity assessment, together with the total size of affected area, which is around 180 km^2. Rockfalls were classified into five categories according to their volume. The volumes of the two largest rockfalls were quantitatively assessed by comparison of Digital Elevation Models to be 15×10^6 m^3 and 3×10^6 m^3. Distribution of very large, large and medium size rockfalls has clearly defined an elliptical zone, elongated parallel to the strike of the seismogenic fault, for which the intensity VII–VIII was assessed. This isoseismal line was compared to the tentative EMS-98 isoseism derived from damage-related macroseismic data. The VII–VIII EMS-98 isoseism was defined by four points alone, but a similar elongated shape was obtained. This isoseism is larger than the corresponding ESI 2007 isoseism, but its size is strongly controlled by a single intensity point lying quite far from others, at the location where local amplification is likely.

The ESI 2007 scale has proved to be an effective tool for intensity assessment in sparsely populated mountain regions not only for very strong, but for moderate earthquakes as well. This study has shown that the quantitative definition of rockfall size and frequency, which is diagnostic for each intensity, is not very precise in ESI 2007, but this is understandable since the rockfall size is related not only to the level of shaking, but also depends highly on the vulnerability of rocky slopes.

1 Introduction

The 12 April 1998 $M_w = 5.6$ Krn Mountains earthquake with maximum intensity VII-VIII EMS-98 (Zupančič et al., 2001) caused extensive damage to buildings in the upper Soča valley region, as well as extensive environmental effects in the Julian Alps. The affected area is located in a sparsely inhabited mountainous environment. The possibility for the application of common intensity scales, which are based on the effects felt by humans, effects on objects and damages to buildings, was therefore limited to the few settlements and villages in the epicentral area. On the other hand, the effects on the natural environment were prominent and widespread. They were described soon after the earthquake (Vidrih and Ribičič, 1999) and a first attempt was made to evaluate their applicability to assess intensities using the EMS-98 scale (Vidrih et al., 2001). In that study it was realized that the EMS-98 scale (Grünthal, 1998) is not sufficiently detailed in the description

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Fig. 1. Location map of the study area with epicentre of 12 April 1998 earthquake.

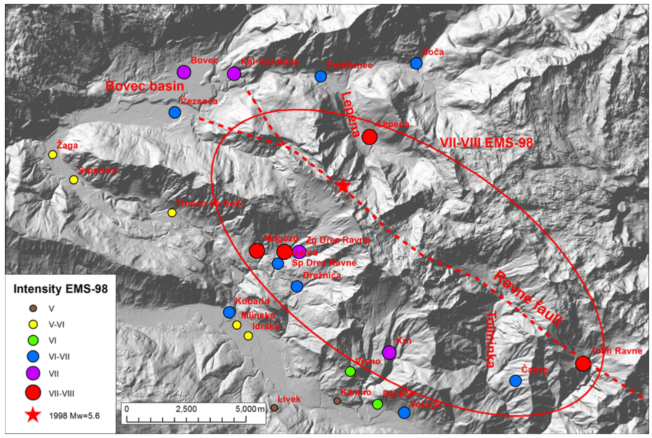

Fig. 2. Intensity map (EMS-98) of 12 April 1998 $M_w = 5.6$ earthquake (data courtesy of Ina Cecić; Zupančič et al., 2001) with tentative VII–VIII EMS-98 isoseismal line. The trace of the causative Ravne fault is also shown.

and evaluation of effects on the natural environment. It is deficient especially in quantitative description of environmental effects characteristic for particular intensity degrees. Introduction of a completely new Environmental Seismic Intensity scale (ESI 2007; Guerrieri and Vittori, 2007) was therefore a major step forward in macroseismic investigations of effects on the natural environment. Prominent environmental effects of the 1998 Krn Mountains earthquake and the recently presented ESI 2007 scale were the main motivation to conduct a new study, which is presented in this paper. It includes a detailed description, classification and evaluation of all environmental effects, a new intensity assessment based on the ESI 2007 scale and a comparison of results with intensity assessment based primarily on damage to buildings according to EMS-98 (Cecić et al., 1999).

ESI 2007 has similar structure as other twelve degree scales. Earthquake environmental effects are divided into primary (surface faulting and deformations) and secondary effects which are generally induced by ground shaking. They are grouped in: hydrological anomalies, anomalous waves, ground cracks, slope movements, tree shaking, liquefaction, dust clouds and jumping stones (Guerrieri and Vittori, 2007). Slope movements which include rockfalls and landslides are among the most important secondary effects in areas with pronounced topography. It is well known that for some earthquakes, especially in Asia and Latin America, they have much more dramatic consequences than ground shaking itself through damming narrow valleys or burying complete settlements or villages. The size (volume) of slope movements is together with their frequency diagnostic for certain intensity to some extent (Table 1). The importance of a scale based on environmental effects lies not only in supplementing other intensity scales, but also in allowing a better comparison among historical and recent earthquakes. ESI 2007 was recently applied to different European earthquakes including 1997 Umbria-Marche (Guerrieri et al., 2009), 2003 Lefkada (Papathanassiou and Pavlides, 2007), 1981 Alkyonides (Papanikolau et al., 2009) as well as for historical earthquakes in the southern Apennines (Serva et al., 2007). How seismic hazard assessment can benefit from the implementation of ESI 2007 was recently studied by Papanikolau (2011).

2 The earthquake on 12 April 1998 in Krn Mountains

The earthquake on 12 April 1998 at 10:55 UTC with $M_w = 5.6$ in Krn Mountains (NW Slovenia, Fig. 1) was one of the strongest events that occurred in Slovenia during the 20th century. It caused extensive damage, mainly in the upper Soča valley, but no casualties. The maximum intensity VII–VIII EMS-98 was observed in four villages (Fig. 2) in the epicentral area (Cecić et al., 1999; Zupančič et al., 2001). The earthquake was followed by an extensive aftershocks sequence (Bajc et al., 2001; Ganas et al., 2008). On 12 July 2004 another strong ($M_w = 5.2$) earthquake occurred in the same area. Its maximum intensity was VI–VII EMS-98. Both earthquakes occurred at a depth of 7.6–11 km on the NW–SE trending near-vertical Ravne fault (Fig. 2), characterized on the surface by prominent segmentation (Kastelic et al., 2006). It was revealed by strong motion inversion that the 1998 event activated a 12 km long segment of this right-lateral strike-slip fault, with a rupture confined between 3 km and 9 km depth which propagated bilaterally within two structural barriers (Bajc et al., 2001). Detailed inspection of the fault trace showed that the earthquake caused no surface rupture. The epicentral distance of both strong earthquakes to the closest towns of Bovec and Kobarid was 6–7 km (Fig. 2).

Large variations in damage to buildings were observed especially in the Bovec (Gosar, 2007, 2008) and Kobarid (Gosar, 2010) basins; these variations were explained by

Table 1. Extraction from the ESI 2007 intensity degrees with description of secondary effects relevant for Krn Mountains 1998 earthquake (after Guerrieri and Vittori, 2007).

Intensity		Slope movements	Total affected area
IV	Largely observed	Exceptionally, rocks may fall and small landslide may be (re)activated along slopes where the equilibrium is already near the limit state, e.g. steep slopes and cuts, with loose and generally saturated soil.	–
V	Strong	Rare small rockfalls, rotational landslides and slump earth flows may take place, along often but not necessarily steep slopes where equilibrium is near the limit state, mainly loose deposits and saturated soil. Underwater landslides may be triggered, which can induce small anomalous waves in coastal areas of sea and lakes.	–
VI	Slightly damaging	Rockfalls and landslides with volume reaching ca. 10^3 m^3 can take place, especially where equilibrium is near the limit state, e.g. steep slopes and cuts, with loose saturated soil, or highly weathered/ fractured rocks. Underwater landslides can be triggered, occasionally provoking small anomalous waves in coastal areas of sea and lakes, commonly seen by instrumental records.	–
VII	Damaging	Scattered landslides occur in prone areas, where equilibrium is unstable (steep slopes of loose/saturated soils, while modest rockfalls are common on steep gorges, cliffs). Their size is sometimes significant (10^3–10^5 m^3); in dry sand, sand-clay, and clay soil, the volumes are usually up to 100 m^3. Ruptures, slides and falls may affect riverbanks and artificial embankments and excavations (e.g. road cuts, quarries) in loose sediment or weathered/fractured rock. Significant underwater landslides can be triggered, provoking anomalous waves in coastal areas of sea and lakes, directly felt by people on boats and ports.	10 km^2
VIII	Heavily damaging	Small to moderate (10^3–10^5 m^3) landslides are widespread in prone areas; rarely they can occur also on gentle slopes; where equilibrium is unstable (steep slopes of loose/saturated soils; rockfalls on steep gorges, coastal cliffs) their size is sometimes large (10^5–10^6 m^3). Landslides can occasionally dam narrow valleys causing temporary or even permanent lakes. Ruptures, slides and falls affect riverbanks and artificial embankments and excavations (e.g. road cuts, quarries) in loose sediment or weathered/fractured rock. Frequent is the occurrence of landslides under the sea level in coastal areas.	100 km^2
IX	Destructive	Landsliding is widespread in prone areas, also on gentle slopes; where equilibrium is unstable (steep slopes of loose/saturated soils; rockfalls on steep gorges, coastal cliffs) their size is frequently large (10^5 m^3), sometimes very large (10^6 m^3). Landslides can dam narrow valleys causing temporary or even permanent lakes. Riverbanks, artificial embankments and excavations (e.g. road cuts, quarries) frequently collapse. Frequent are large landslides under the sea level.	1000 km^2
X	Very destructive	Large landslides and rockfalls ($>10^5$–10^6 m^3) are frequent, practically regardless of equilibrium state of slopes, causing temporary or permanent barrier lakes. River banks, artificial embankments, and sides of excavations typically collapse. Levees and earth dams may also incur serious damage. Frequent are large landslides under the sea level in coastal areas.	5000 km^2
XI	Devastating	Large landslides and rockfalls ($>10^5$–10^6 m^3) are frequent, practically regardless of equilibrium state of slopes, causing many temporary or permanent barrier lakes. River banks, artificial embankments, and sides of excavations typically collapse. Levees and earth dams incur serious damage. Significant landslides can occur even at 200–300 km distance from the epicenter. Frequent are large landslides under the sea level in coastal areas.	10 000 km^2
XII	Completely devastating	Large landslides and rockfalls ($>10^5$–10^6 m^3) are frequent, practically regardless to equilibrium state of the slopes, causing many temporary or permanent barrier lakes. River banks, artificial embankments, and sides of excavations typically collapse. Levees and earth dams incur serious damage. Significant landslides can occur at more than 200–300 km distance from the epicenter. Frequent are very large landslides under the sea level in coastal areas.	50 000 km^2

prominent site and resonance effects between soft sediments and buildings. Apart from substantial damage to nearby settlements, the 1998 earthquake caused considerable changes to the landscape through many rockfalls and some landslides (Vidrih and Ribičič, 1999; Vidrih et al., 2001; Mikoš et al., 2006; Vidrih, 2008). On the other hand, the 2004 earthquake had only minor effects (a few rockfalls) on the natural environment. Since the second earthquake was smaller than the first one, this is not a surprise. Nevertheless, the 2004 earthquake caused one death in Krn Mountains, a mountaineer hit by a falling stone.

The upper Soča valley is located in one of the three areas with the highest seismic hazard in Slovenia, although the seismicity before the 1998 earthquake in the Julian Alps was relatively low. According to the seismic hazard map of Slovenia for a 475-yr return period (Lapajne et al., 2001) a peak ground acceleration value in the western part of the Krn mountains is 0.225 g and in the eastern part 0.200 g. This is mainly due to the proximity to the seismically active area of Friuli located 30–40 km westward in northeastern Italy. In this area the 1976 Friuli $M_w = 6.4$ earthquake produced intensities as high as VIII EMS-98 in some Slovenian settlements located close to the border. NW Slovenia and the Friuli region are located at the kinematic transition between E–W striking thrust faults of the Alpine system (Friuli earthquakes) and NW–SE striking right-lateral strike-slip faults of the Dinarides system (Krn Mountains earthquakes). The strongest earthquake ever recorded in the Alps-Dinarides junction area was the 1511 western Slovenia $M = 6.8$ earthquake. The true location and mechanism of this event are still debated (Fitzko et al., 2005; Camassi et al., 2011), due to the early date of occurrence.

3 Seismic effects on natural environment and intensity scales

The twelve degrees macroseismic intensity scales, developed since the beginning of 20th century, were based on evaluation of the effects on humans, manmade structures and the natural environment. However, in the early versions of these scales, the effects of the earthquakes on the natural environment were scarcely included. Their presence in the scale was mostly due to the many references to ground cracks, landslides and landscape modifications contained in the historical reports (Guerrieri and Vittori, 2007). Later, in the second half of the 20th century, these effects have been increasingly disregarded in the literature and in the practice of macroseismic investigations, probably due to their intrinsic complexity and variability requiring specific skills and knowledge, while increasing attention has been put on the apparently easier analysis of effects on humans and manmade structures. Moreover, environmental effects are dependent on stability and vulnerability of slopes, which are more difficult to evaluate than vulnerability of buildings. Recent studies offered new evidence that coseismic environmental effects provide precious information on the earthquake intensity field, complementing the traditional damage-based macroseismic scales. Therefore, the definition of the intensity degrees can effectively take advantage of the diagnostic characteristics of the effects on natural environment (Guerrieri and Vittori, 2007).

The macroseismic scale EMS-98, which is nowadays predominantly used in Europe, considers four categories of effects: on humans, objects, damage to buildings and to the natural environment (Grünthal, 1998). Its basic advantage in comparison to previous scales is a definition of vulnerability classes for buildings and more precise statistical treatment of collected macroseismic data. This quantification is elaborated in details for the first three effects, but not for environmental effects which are rather briefly described in EMS-98. Environmental effects are divided into four groups: (a) hydrological effects, (b) slope failure effects, (c) processes on flat ground (cracks, fissures), and (d) convergent processes/complex cases (liquefaction). For each type of effects three intensity ranges are presented in tabular form: (a) the possible range of observations, (b) the range of intensities that is typical for this effect, and (c) the range of intensities for which this effect is most usefully employed as a diagnostic (Grünthal, 1998). One of the main problems of this table is that the same phenomenon is ascribed to a very wide range of intensity degrees, which prevents its practical use in assessing intensities. Therefore, Vidrih et al. (2001) proposed a different approach, reducing the intensity extent of phenomena appearance by introducing, in analogy to buildings, terrain vulnerability regarding earthquakes, the frequency of appearance and the level of damage with individual phenomena.

In 2007 the Environmental Seismic Intensity scale (ESI 2007) was introduced as a new scale based only on the effects triggered by earthquakes on the natural environment (Guerrieri and Vittori, 2007). It follows the same basic structure as any other twelve degree scale. It was developed by a working group of the International Union of Quaternary Research (INQUA) Subcomission on paleoseismicity. It is believed that the use of ESI 2007 affords a better picture of macroseismic fields, because only environmental effects allow comparison of the earthquake intensity both in time, since they are comparable for a much larger time window than the period of instrumental recordings, and in different geographic areas, as they do not depend on different building practices. Therefore, its application can contribute to the seismic hazard studies in different areas (Papanikolaou, 2011).

Earthquake environmental effects are, according to ESI 2007, categorized as primary and secondary effects. Primary effects are the surface expression of the seismogenic tectonic source and they include surface faulting, uplift and subsidence. They are typically observed for crustal earthquakes over a certain magnitude threshold. Secondary effects are phenomena generally induced by ground shaking: ground cracks, slope movements (rockfalls and landslides), liquefaction phenomena, anomalous waves (seiches), hydrogeological anomalies and tree shaking. The occurrence of secondary effects is commonly observed in a specific range of intensities. For each type the ESI 2007 describes their characteristics and size as a diagnostic feature in a range of intensity degrees. ESI 2007 specifies also the typical area affected by environmental effects and the type of record (geological, geomorphological). Secondary effects with geological and geomorphological records are: ground cracks, slope movements, liquefaction and anomalous waves/tsunamis. Secondary effects with minor geological records are hydrogeological anomalies and tree shaking. For intensity equal to or lower than IX, the main goal of the ESI 2007 scale is to bring the environmental effects in line with other damage indicators. In this range it should be mainly used along with other scales. In the range between X and XII, the distribution and size of environmental effects, especially primary tectonic features, becomes the most diagnostic tool to assess the intensity level. The use of ESI 2007 alone is recommended only when effects on humans and buildings are absent or too scarce (i.e. in sparely populated areas), or if these saturate (intensities X to XII) loosing their diagnostic value (Guerrieri and Vittori, 2007).

4 Methods applied

Extensive effects of the 12 April 1998 earthquake on the natural environment, which were spread over a relatively large area, required a systematic approach in data collection and analysis. This was particularly important because the wider epicentral area belongs to the high mountains of Julian Alps where access by car is limited to a few valleys only. Therefore I decided on a combination of data collection and analysis based on three different approaches: field survey, analysis of aerial photography images and macroseismic questionnaires.

The principal approach for data collection was a field survey of all effects on the natural environment. Rockfalls and landslides were systematically surveyed and documented in the few months after the earthquake and a database of rockfalls prepared. There were some reports of smaller rockfalls triggered by aftershocks, mainly at the locations of previous large rockfalls. Therefore, they can not bias the performed analyses.

The Surveying and Mapping Authority of Slovenia had already planned to carry out the periodic aerial photography survey of the NW part of Slovenia in July 1998, three months after the earthquake. This was fortunate, because without additional expenses, aerial photography images were acquired and became available only a few months after the earthquake. This is a crucial matter, since the recognition of rockfalls and landslides is much easier when the newly exposed surfaces or rock debris and blocks are still fresh, because lichens and vegetation quickly start to change the exposed surfaces. The original scale of the aerial survey was 1:17 500. Stereo pairs of aerial images were analysed by using stereo glasses for a 3-D view. Later, images were transformed into Digital Ortho Photos (DOF) which enabled their analysis by using GIS software as well.

Table 2. Distribution of rockfalls according to their size.

Size of rockfall	Estimated volume (m^3)	Number
very small	10^2	53
small	10^3	13
medium	10^4	6
large	10^5	4
very large	$>10^6$	2

One important topic of ESI 2007 regarding slope movements is the quantitative assessment of rockfall and landslide size (volume). For landslides this is usually easier, because we can measure the area and estimate/measure the average thickness of the landslide body. For rockfalls, which are much more irregular than landslides (with large variations in the thickness of masses of fallen rocks), estimation of the actual volume is usually more difficult and requires a lot of experience to avoid large errors. Therefore I tried to quantitatively assess/measure at least the volume of the two largest rockfalls. I found that this was possible by using Digital Elevation Models (DEM). Until 1998 in Slovenia, only a low resolution 100 m grid DEM was available. Based on the aerial photography images acquired in July 1998, a new 25 m resolution DEM was prepared. The comparison of DEMs showed the topography before and after the earthquake and enabled estimation of the volume of fallen rocks.

After the earthquake, the Slovenian seismological service (Geophysical Survey of Slovenia) sent more than 4300 macroseismic questionnaires to all volunteer observers located throughout Slovenia, of which 2900 were returned (Cecić et al., 1999). The questionnaire contained two questions about hydrological effects. In addition, all observers were asked to communicate any additional observation or remark. All the answers were carefully inspected and several descriptions of effects on the natural environment analysed. Macroseismic data were later exchanged also with the neighbouring countries (Italy, Austria) (Cecić et al., 1999; Zupančič et al., 2001), but no effects on the natural environment were reported by these countries.

5 Rockfalls and other effects on mountain slopes and flat ground

Detailed field inspection and analysis of aerial images showed that the earthquake caused 78 rockfalls in the upper Soča valley and Krn Mountains (Fig. 3). They were classified

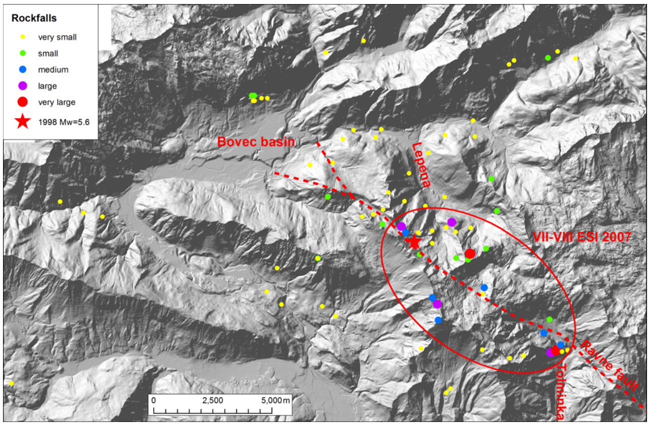

Fig. 3. Distribution of rockfalls caused by 12 April 1998 earthquake in Upper Soča valley with VII–VIII ESI 2007 isoseismal line.

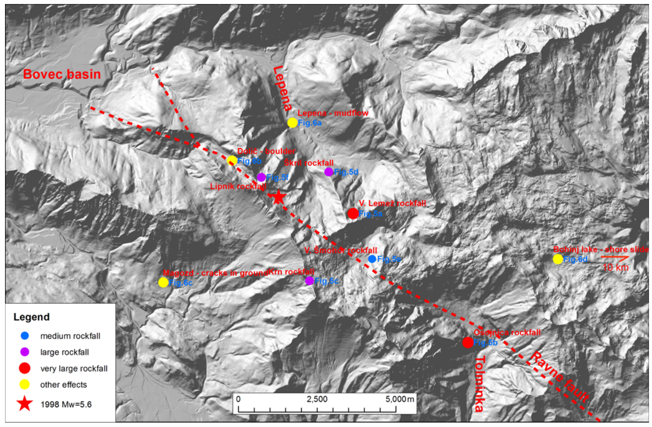

Fig. 4. Location map of rockfalls and other environmental effects shown in Figs. 5 and 6.

according to their estimated volume into five groups (Table 2): very small, small, medium, large and very large. The total size of the affected area is around 15 × 12 km, which is 180 km^2. Distribution of very small (10^2 m^3) rockfalls which predominate in number (53) is very uneven. This was expected because it depends mainly on the geological setting and on the terrain slope. On the other hand medium to very large rockfalls are clearly distributed in a zone approximately 5 km wide and 9 km long, which is elongated in a NW–SE direction, along the seismogenic Ravne fault (Fig. 3). The density of rockfalls is very uneven, depending on the spatial distribution of rockfall-prone slopes. On average there were three rockfalls per km^2 in the whole affected area, but the range is from one rockfall at larger distances from the epicentre to more than five rockfalls per km^2 in the closest epicentral area. It is interesting that the termination of rockfalls occurrence is very sharp to the SE of the epicentre, in the Tolminka valley, but more gradual to the NW, W and N. It is known from strong motion inversion that the Ravne fault ruptured for a length of 12 km between the Bovec basin in the NW and the Tolminka spring basin in the SE (Bajc et al., 2001). Along the same segment the majority of the rockfalls occurred.

Two rockfalls were classified as very large (>10^6 m^3) (Figs. 3 and 4). The largest one occurred on V. Lemež in the Lepena valley (Fig. 5a), at a distance of 1.5 km from the epicentre and 0.8 km from the fault trace. By comparing two DEMs which show topography before and after the earthquake, its volume was estimated as 15 × 10^6 m^3 (Fig. 7). The maximum depth of the rockfall scar (thickness of collapsed rocks) is 120 m. The mixture of rocks and snow reached the Lepena valley, where the associated air blast caused the collapse of trees in a forest in a 15 m wide and 500 m long corridor and even caused a wooden shed to fall from its base. The second largest rockfall occurred on the Osojnica Mountain above the Tolminka valley (Fig. 5b), at a distance of 6 km from the epicentre and 0.6 km from the fault trace. By comparing DEMs before and after the earthquake its volume was estimated as 3 × 10^6 m^3 (Fig. 8). The maximum depleted thickness was about 80 m. This was the most spectacular rockfall, because the whole SE face of the mountain, which is 500 m high and 600 m wide, collapsed. The forest at the mountain toe was completely destroyed and buried by rocky blocks and debris.

There were four rockfalls classified as large (10^5 m^3) (Fig. 4). Along the slopes of the Krn and Krnčica Mountains several huge planar rockslides occurred (Fig. 5c), developed along cracks or bedding planes within limestone dipping downslope. The Škril rockfall (Fig. 5d), which is a typical example of a wedge-shaped rockslide, occurred at the intersection of two joints whose line dips along the slope (Vidrih et al., 2001). The Lipnik rockfall (Fig. 5f) is the large rockfall closest to the epicentre. The SW face of the mountain there collapsed along with some tunnels and caverns excavated during the World War I. The known Soča war front runs across the whole of the Krn Mountains and several war monuments and ruins were damaged by the earthquake. There were six rockfalls of medium size (10^4 m^3). A typical example is the V. Šmohor rockfall (Fig. 5e), where the top of the mountain collapsed, although the slope was not too steep (less than 30°).

Beside rockfalls some other slope and flat-ground effects occurred in the region. There were some landslides, but since carbonate outcrops predominate in the area, the landslides were limited to river banks, glaciofluvial sediments and to some hilly flysch. An outstanding example of a mudflow occurred in the Lepena valley (Figs. 4 and 6a). At the time of the earthquake there was a large amount of fresh snow in the high mountains, very prone to produce avalanches. The mudflow was generated by a mixture of soil, rock and snow that slid down along a steep ravine as an avalanche. When the rapid mudflow reached the valley floor, the debris was deposited in a fan shape. Several individual boulders also rolled down the slopes. They caused extensive damage to the

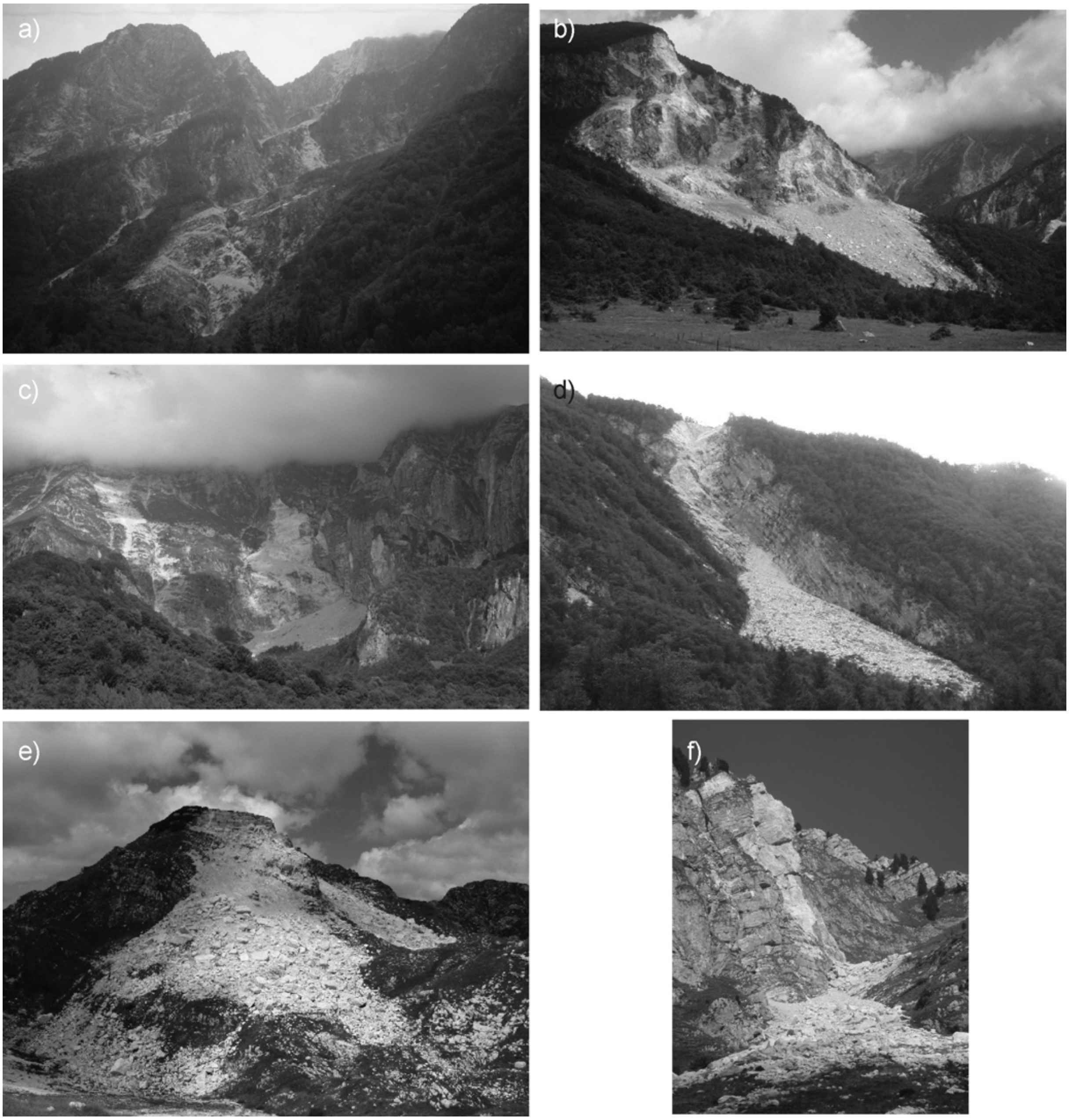

Fig. 5. Selection of largest rockfalls with assigned intensities in brackets. **(a)** V. Lemež (VIII), **(b)** Osojnica (VIII), **(c)** Krn (VII), **(d)** Škril (VII), **(e)** V. Šmohor (VI), **(f)** Lipnik (VII).

forest, reaching some roads and destroying a car parked in the Soča valley. The largest boulder (Fig. 6b), whose volume was around 200 m^3, was observed in the Lipnik rockfall (Fig. 5f); it rolled down the Dolič valley without breaking into fragments. There were only few reports on cracks in the ground, and none of them could be interpreted as a surface faulting. The example of ground cracks shown in Fig. 6c is from Magozd, where the intensity was assessed as VII–VIII EMS-98. At the Bohinj lake which is located 25 km east of the epicentre, the shore built of glaciofluvial debris slid into the water (Fig. 6d). Field inspection showed no evidence of liquefaction. Therefore, it was interpreted as a pure sliding effect. This is believable, because the intensity in this area assessed from damage to buildings was VI EMS-98, and liquefaction is very unlikely at this intensity. On the other hand, sliding along shorelines and river banks during earthquake is a common effect.

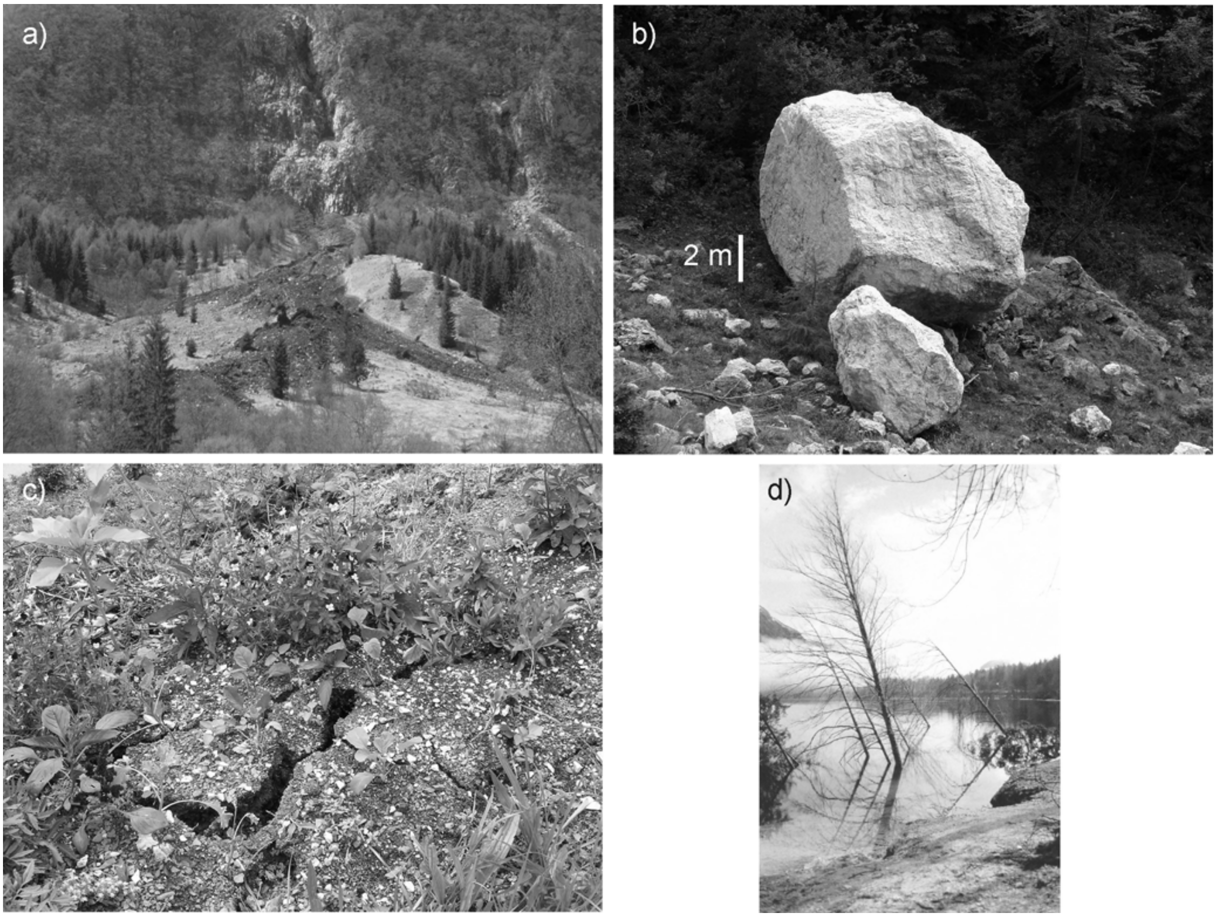

Fig. 6. Selection of other environmental effects. **(a)** Mudflow in Lepena valley; **(b)** huge boulder in Dolič; **(c)** cracks in ground in Magozd; **(d)** Bohinj lake shore slide.

6 Hydrological effects

In our macroseismic questionnaires there were two questions on hydrological effects. There were 31 positive answers to the first question "Was there a change in springs and water wells?", 25 from the upper Soča valley and 4 from the Bohinj area. Nobody described the observed effects in more detail, but some responders reported the change of the water colour and two observers reported the water stopped flowing out at two springs, but they didn't give more insights. On the other hand there were no reliable reports on the change of flow from springs in the epicentral area, as would be diagnostic feature for intensities VII or higher on the ESI 2007 scale. However, it should be considered that the assessment of this effect wasn't easy due to the bad weather conditions during the earthquake sequence with heavy rainfall in the lowlands and snow falling in highlands. The outflow out of springs was therefore very high. There were several reports on the change of water colour in creeks especially for the Lepenca and Tolminka rivers (Fig. 4), but nobody was present at their springs at the time of the earthquake to ascertain whether or not it was due to occurrence of landslides and rockfalls. In case of the Lepenca River a very large rockfall from V. Lemež, described in detail above, partly reached the stream bed. Therefore, the water remained coloured for several weeks after the earthquake. A red water colour was reported for the Tolminka River, but this phenomenon cannot be easily explained. Although there was a very large rockfall from Osojnica (described above), only a few blocks reached the stream bed. On the other hand only small landslides were reported close to Tolminka River. Whether or not the Tolminka colouring occurred just at the spring or somewhere along the river course remained an open question.

No positive answer to the second question "Do waves occur on large water surfaces?" was reported. There are two large lakes close to the epicentre, the artificial Most na Soči Lake close to Tolmin and the natural Bohinj Lake. It is probable that waves occurred in both lakes, but nobody reported them. This is believable, because the weather was rainy and the earthquake occurred on Easter Sunday at 12:55 local time when most people were at home for lunch. At Bohinj Lake a shore strip, about 100 m long, slid down into the lake, which

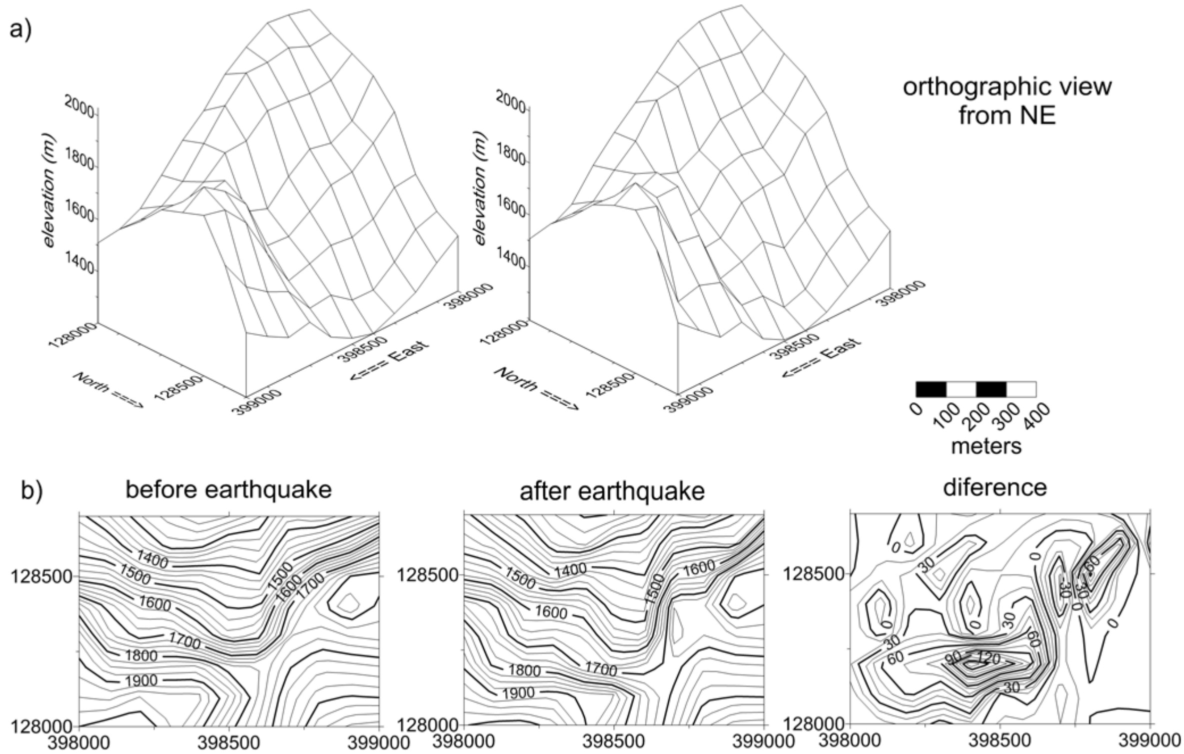

Fig. 7. Digital elevation model of V. Lemež mountain showing pre- and post-earthquake topography in **(a)** perspective view and **(b)** contour maps together with the map of differences between both models.

would almost certainly have caused waves on its surface. Therefore, if there had been eyewitnesses, it wouldn't have been possible to discriminate between seiches and gravitational water waves.

It's worth noting that the earthquake had significant effects on underground water levels in aquifers of Sorško and Kranjsko polje, located 60 km east of the epicentre. The fluctuations in groundwater levels coincident with the earthquake, ranged from 23 to 82 cm, as recorded by four piezometres (Uhan and Gosar, 1999). No fluctuation was recorded before or after the earthquake, and no other fluctuations were reported from elsewhere. Therefore, it isn't possible to provide an interpretation of the observed effects in Sorško and Kranjsko polje aquifers.

7 Intensity assessment

After careful inspection, classification and evaluation of all environmental effects due to the 1998 earthquake, the next step has been to study how these data can be used for the assessment of site intensity. Rockfalls was the only widespread effect in the area. Therefore, it was decided to use this effect alone, including the size of total affected area, which was around 180 km^2. This area extent corresponds to the VIII intensity degree in ESI 2007, which provides a total affected area on the order of 100 km^2 for intensity VIII and 1000 km^2 for intensity IX (Table 1). No reliable reports on hydrological effects that could be used for an intensity refinement were obtained.

The ESI 2007 scale seems to be fairly incomplete in the quantitative description of slope movements (Table 1). Only for intensity VIII does it differentiates between expected volume of "widespread" landslides (10^3–10^5 m^3) and "sometimes large" (10^5–10^6 m^3) rockfalls. At intensity VII, the volume of landslides and rockfalls is qualitatively and quantitatively qualified together as "sometimes significant" (10^3–10^5 m^3). The same is true for intensity IX at which both slope movements can be "frequently large" (10^5 m^3) and "sometimes very large" (10^6 m^3). For intensity X large ($>10^5$–10^6 m^3) landslides and rockfalls are "frequent" (Guerrieri and Vittori, 2007). It seems therefore that the volume of rockfalls and their frequency are not unequivocally diagnostic for intensity assessment in the range VII–IX. A shortcome of the ESI 2007 scale is the absence of quantitative description of the likelihood of landslides and rockfalls occurrence through the definition of slope vulnerability.

Taking into account the problem of a diagnostic size and frequency of rockfalls, it was decided to apply a preliminary assignment from the previously used distribution of rockfalls according to their size (Table 2, Fig. 3). As a working hypothesis it was decided to assign an intensity degree VIII to very large ($>10^6$ m^3) rockfalls, an intensity degree

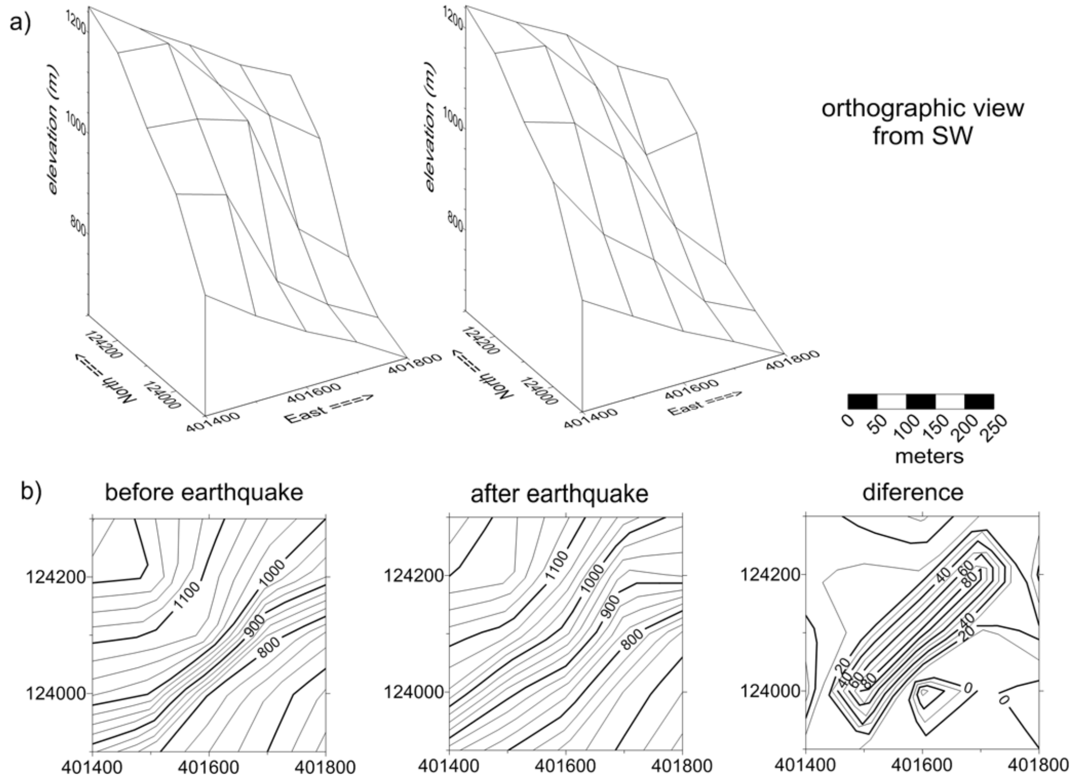

Fig. 8. Digital elevation model of Osojnica mountain showing pre- and post-earthquake topography in **(a)** perspective view and **(b)** contour maps together with the map of differences between both models.

VII to large (10^5 m^3) rockfalls and an intensity degree VI to medium (10^4 m^3) rockfalls. It was concluded that small and very small rockfalls could not be used as diagnostic for intensity assessment in this case. Considering also the frequency of rockfalls for each size, a tentative isoseismal line for intensity VII–VIII has been drawn (Fig. 3). Since there were only two very large rockfalls and four large ones, an intensity VIII cannot be justified, whereas an intensity assessment VII–VIII is more suitable. The isoseismal line was drawn in such a way that it includes all large and very large rockfalls. It has a clear elliptical shape elongated along the strike of the seismogenic Ravne fault. It is 9.5 km long and 5.5 km wide. This line includes also all six rockfalls classified as medium size. Unfortunately, it was not possible to avoid this, because all medium size rockfalls are located very close to large and very large rockfalls (Fig. 3). It means that in the case of this earthquake, it is not possible to use medium size rockfalls as diagnostic for intensity degree VI, as was a working hypothesis. Moreover, the environmental effects alone, don't allow drawing intensity isolines equal and lower than VII. On the other hand, the total affected area, as the second relevant criteria of ESI 2007 scale, can't alone justify the maximum intensity of VIII for this earthquake.

For EMS-98 intensities shown in Fig. 2 no isoseismal lines were available (Cecić et al., 1999; Zupančič et al., 2001). In Zupančič et al. (2001) only the average radii of areas of the same intensity are given, which are 13 km for intensity VII and 25 km for intensity VI, but the average radius is not specified for intensity VII–VIII. This is methodologically correct, because it is not a standard practice to draw isoseisms for "half" degrees of intensity and because there are only four points with VII–VIII intensity. Nevertheless, for the purpose of comparison a tentative VII–VIII EMS-98

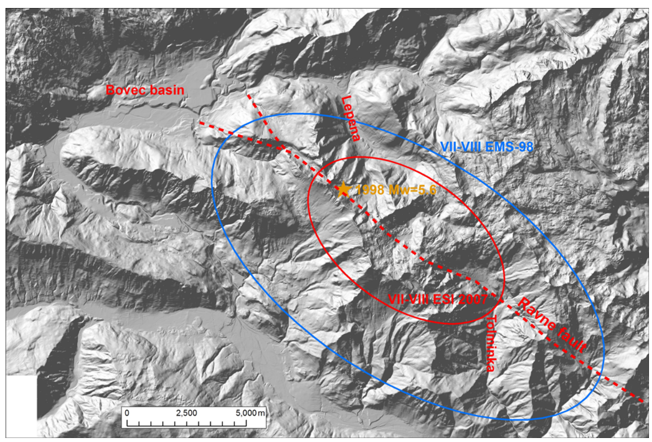

Fig. 9. Comparison of two isoseisms for 1998 earthquake: tentative VII–VIII EMS-98 isoseism from macroseismic data and VII–VIII ESI 2007 isoseism from environmental effects.

isoseismal line was drawn in Fig. 2. It was drawn in such a way that it just includes all four villages with intensity VII–VIII. Also this isoseism has a clear elliptical shape elongated parallel to the strike of the Ravne fault and it is 18 km long and 9.5 km wide. Its size is strongly controlled by a single point (Tolminske Ravne) laying quite far from others to SE. Moreover, Tolminske Ravne are located on a glacial moraine, on which moderate site effects are expected that very likely enhanced the intensity. Therefore, this isoseismal line cannot be considered too reliable.

8 Conclusions

Both intensity assessments of the 12 April 1998 $M_\mathrm{w} = 5.6$ 1998 earthquake, first based on effects on humans, on objects and on damage to buildings according to EMS-98 (Cecić et al., 1999; Zupančič et al., 2001), and the second one based on environmental effects according to ESI 2007 from this study, have shown that the maximum intensity of the earthquake was VII–VIII. The total affected area and two very large rockfalls could indicate an intensity as high as VIII, but I conclude that the criteria of total affected area alone and two other observations are not enough to justify this higher maximum intensity. This study has shown also that the ESI 2007 scale can not be used alone for intensities lower than IX, but always in combination with other intensity scales, preferably with EMS-98, because in both scales a frequency of observed phenomena is also included. Both methods of intensity assessment have shown a clear oval shape of the largest intensity (VII–VIII) isoseism elongated along the strike of the seismogenic Ravne Fault (Fig. 9). The areas enclosed by the two isoseismal lines are different, but this can be explained by the fact that the area within the EMS-98 isoseism is strongly controlled by a single intensity point lying quite far to the SE (Fig. 2), at the location where local amplification is likely. On the other hand the area of ESI 2007 isoseism seems to be better defined by the distribution of very large and large rockfalls (Fig. 3). The difference can be explained by the occurrence of the earthquake in very sparsely populated area, which limits the EMS-98 intensity assessment to the few settlements and villages. Few medium size rockfalls cannot be used to draw lower intensity isoseism (VII) in case of this earthquake, because they are all located very close to large and very large rockfalls.

The ESI 2007 scale has proved to be an effective tool for intensity assessment for moderate earthquakes, not only for very strong earthquakes where environmental effects are dominant and widespread. The new scale is especially valuable in such sparsely populated regions as the Julian Alps. In this high mountain environment built of carbonates, rockfalls are the most frequent environmental effect, whereas landslides and other effects occur much more rarely. The quantitative definition of rockfall size and frequency, which are diagnostic for each intensity is not very precise in ESI 2007, but this is comprehensible, since rockfall size is related not only to the level of shaking, but depends highly on the vulnerability of the slopes. Rock vulnerability issues and their influence on intensity assessment were further evaluated by Vidrih et al. (2001).

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